THE ANTARCTIC OZONE HOLE

RICHARD S. STOLARSKI

NASA GODDARD SPACE FLIGHT CENTER

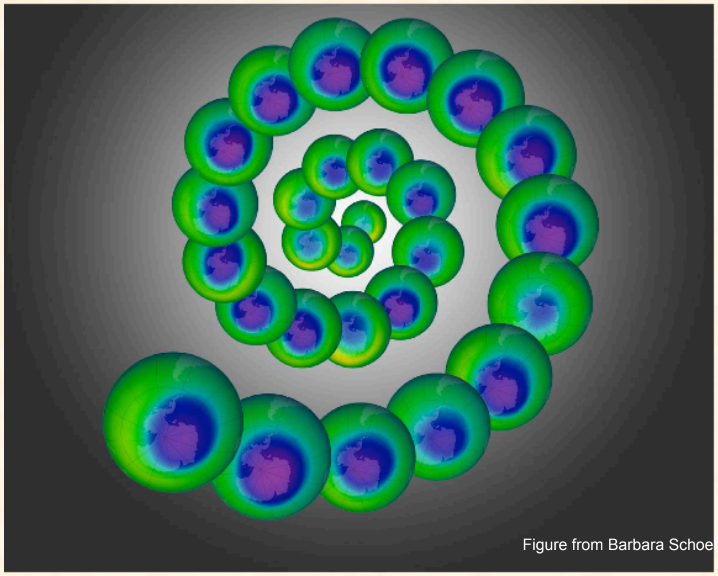


Figure from Barbara Schoe

Emphasizing the role of measurements from satellites

NASA Earth System Science at 20 SYMPOSIUM

What do we get from satellites?

Perspective !

A Global View

BACKGROUND AND HISTORY

Four lines of history converge on the fluorocarbon-ozone issue and the ozone hole

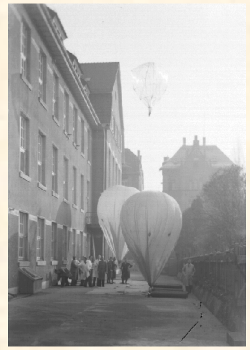
- **Discovery and measurement of stratospheric ozone**
- **Laboratory studies of the chemical properties of molecules that affect ozone**
- **Synthesis and development of chlorofluorocarbons (CFCs)**
- **Development of basic understanding of stratospheric dynamics, meteorology, and ozone**

Some Ozone Measurement History

Charles Fabry

Gordon Dobson

Ground-based



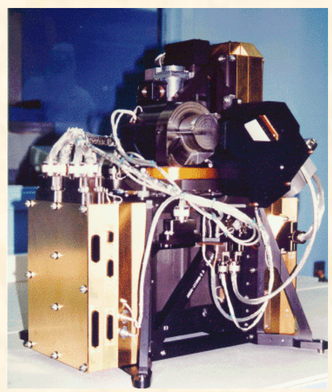
Erich Regener
1881-1955

Victor Regener
1913-2006

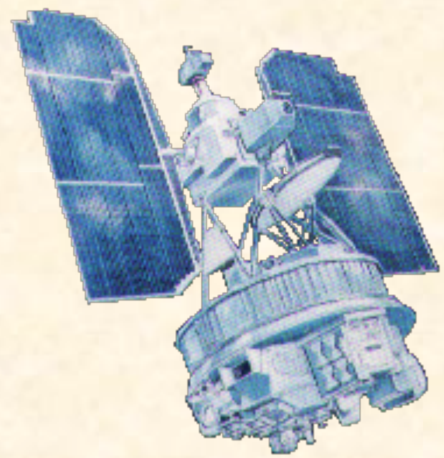
Balloon

ER 2

Aircraft



TOMS



Nimbus 7

Satellite

Some Chemistry History

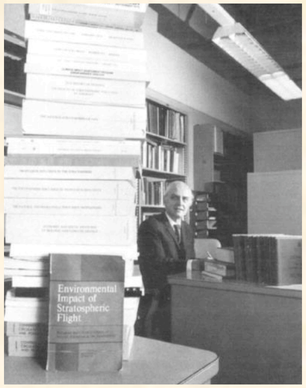
Early work: study of ozone photochemistry in the laboratory

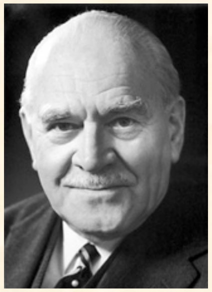
Fritz Weigert (1907) noted that addition of Chlorine (Cl_2) sped up rate of ozone recombination – work was contemporary with early work on photosynthesis and on the photoelectric effect

Paul Crutzen, in 1970, developed the early theory of the catalytic impact of nitrogen and hydrogen oxides on stratospheric ozone

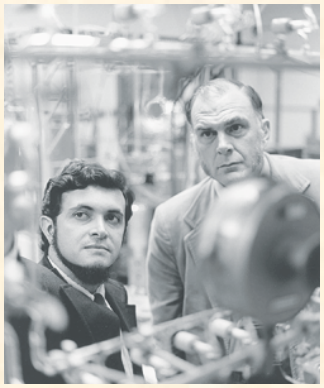
Sydney Chapman proposed the first ozone theory for the stratosphere in 1930

Harold Johnston, in 1971, suggested that nitrogen oxides from proposed SSTs could deplete stratospheric ozone – CIAP program followed



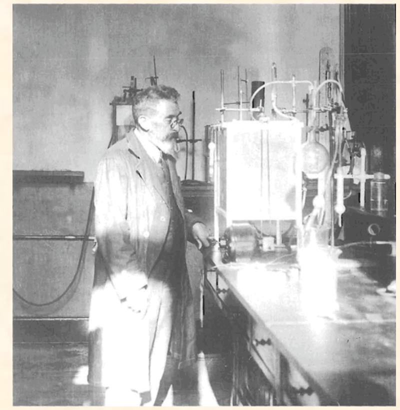


Norrish and Porter – Nobel prize in chemistry 1967 for techniques to detect small concentrations of short-lived radicals



Molina and Rowland proposed that stratospheric ozone could be destroyed by chlorine released in the stratosphere from CFCs in 1974

Early Synthesis of CFCs

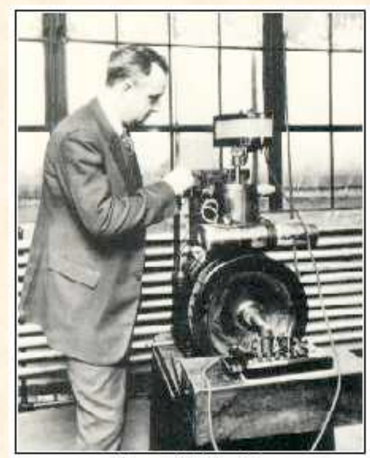


Frederic Swarts

Belgian chemist: (1866 -1940). Swarts was one of only about a half dozen fluorine chemists in the world in the late part of the 19th century; he prepared the first chlorofluorocarbon, CFC-11 in the early 1890s.

$SbF_3Br_2 + CCl_4 \rightarrow CFCl_3$ (CFC-11) $+ SbF_2Br_2Cl$

CCl_4 synthesized in 1839 by Regnault



Thomas Midgley, Jr.

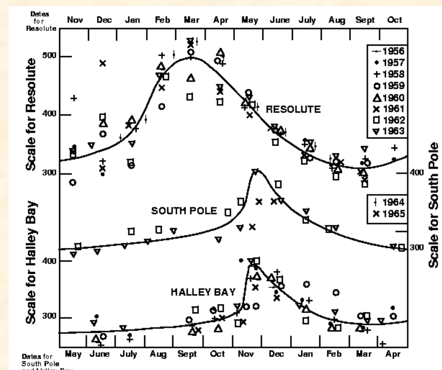
Thomas Midgley, Jr

1930: GM charged Midgley with developing a non-toxic and safe refrigerant for household appliances. He (along with Charles Kettering) synthesized dichlorodifluoromethane ($CHCl_2F$). CFCs replaced sulfur dioxide, methyl chloride or ammonia gases (toxic or explosive substances) previously used in heat pumps and refrigerators.

Stratospheric Meteorology, Dynamics, and Ozone

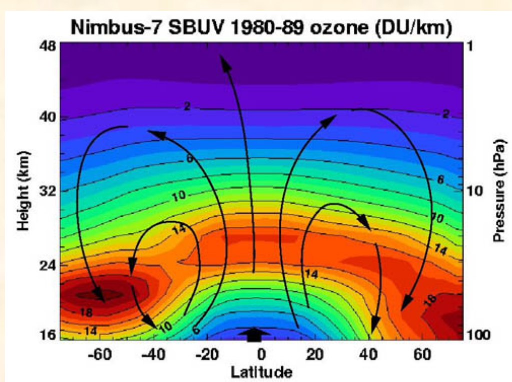
Léon Teisserenc de Bort discovers the stratosphere – a layer in which temperature no longer decreases with altitude

Unique nature of Antarctic vortex is revealed during the IGY 1957-8



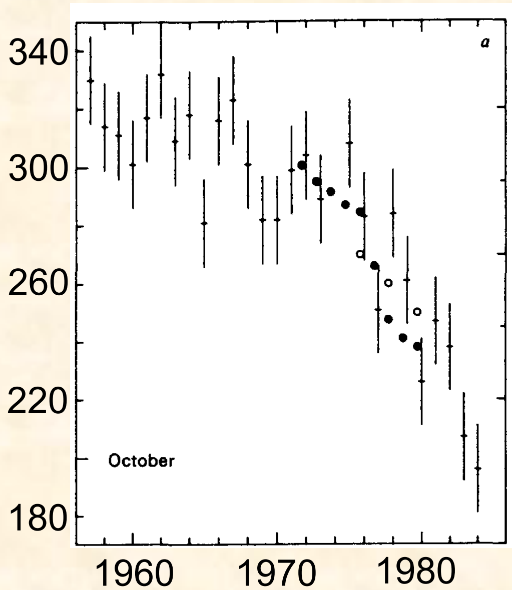
Dobson summarizes (1966) ozone measurements of IGY showing clear difference between Antarctic and Arctic

Brewer-Dobson Circulation (1951)helps explain water vapor and ozone distributions in the stratosphere



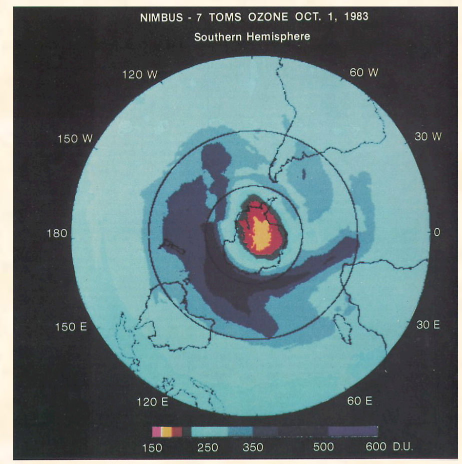
Polar Stratospheric Clouds are shown to be a ubiquitous feature of the winter Antarctic stratosphere

Ozone Hole Discovery

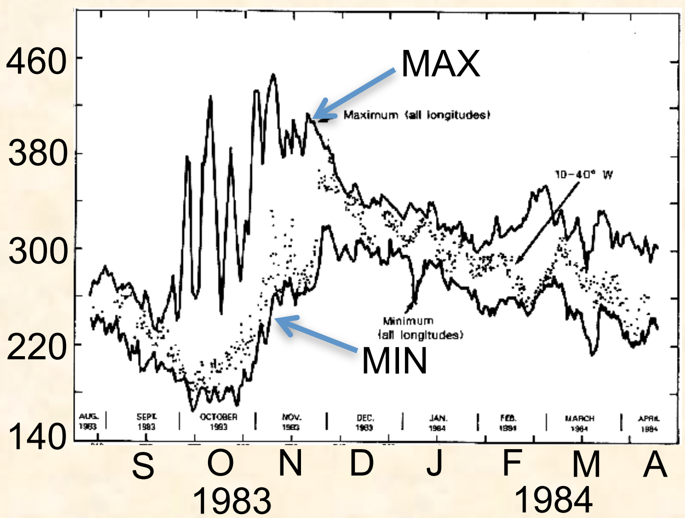


Farman, Gardiner, & Shanklin (1985)

Discovered at the British Antarctic Survey station at Halley Bay from measurements begun during the IGY

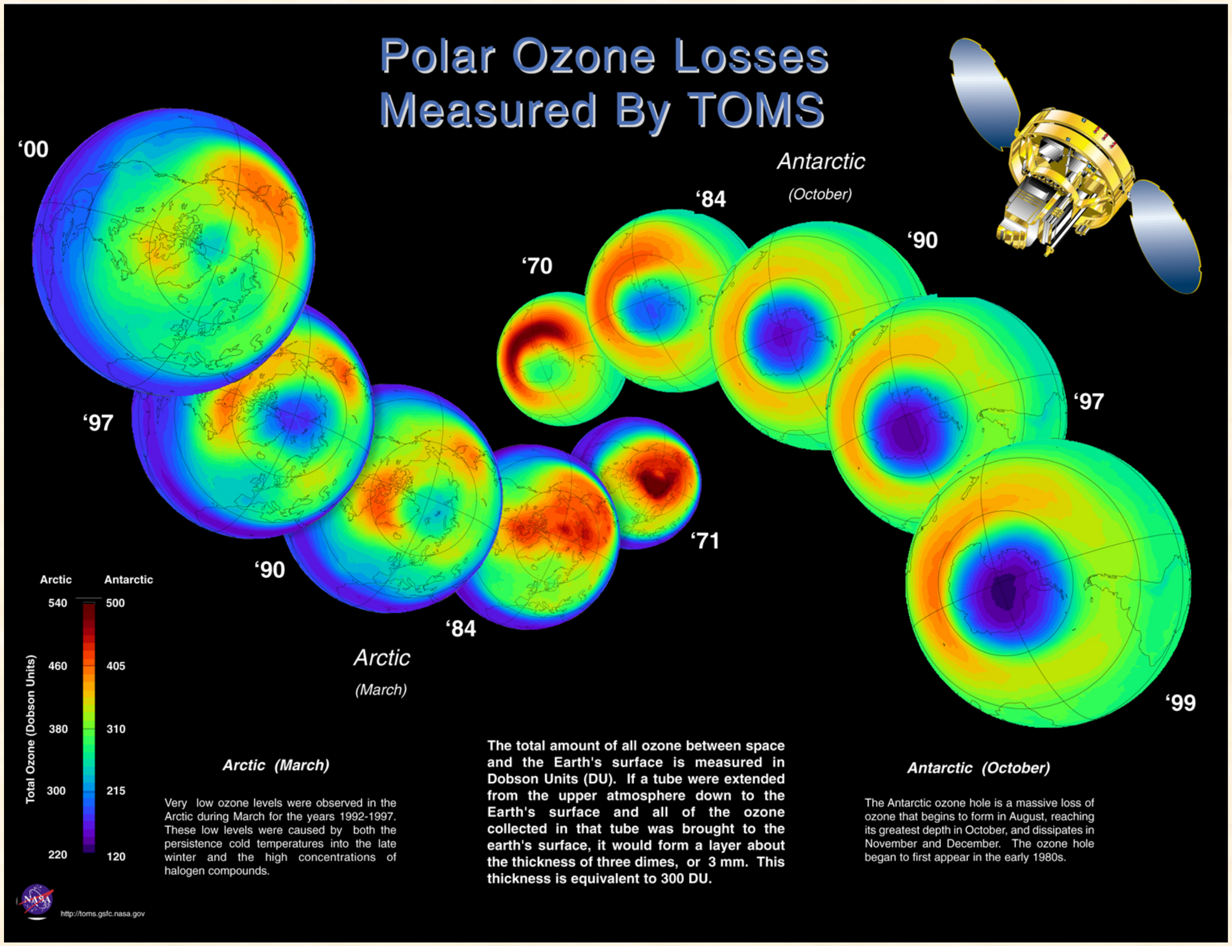


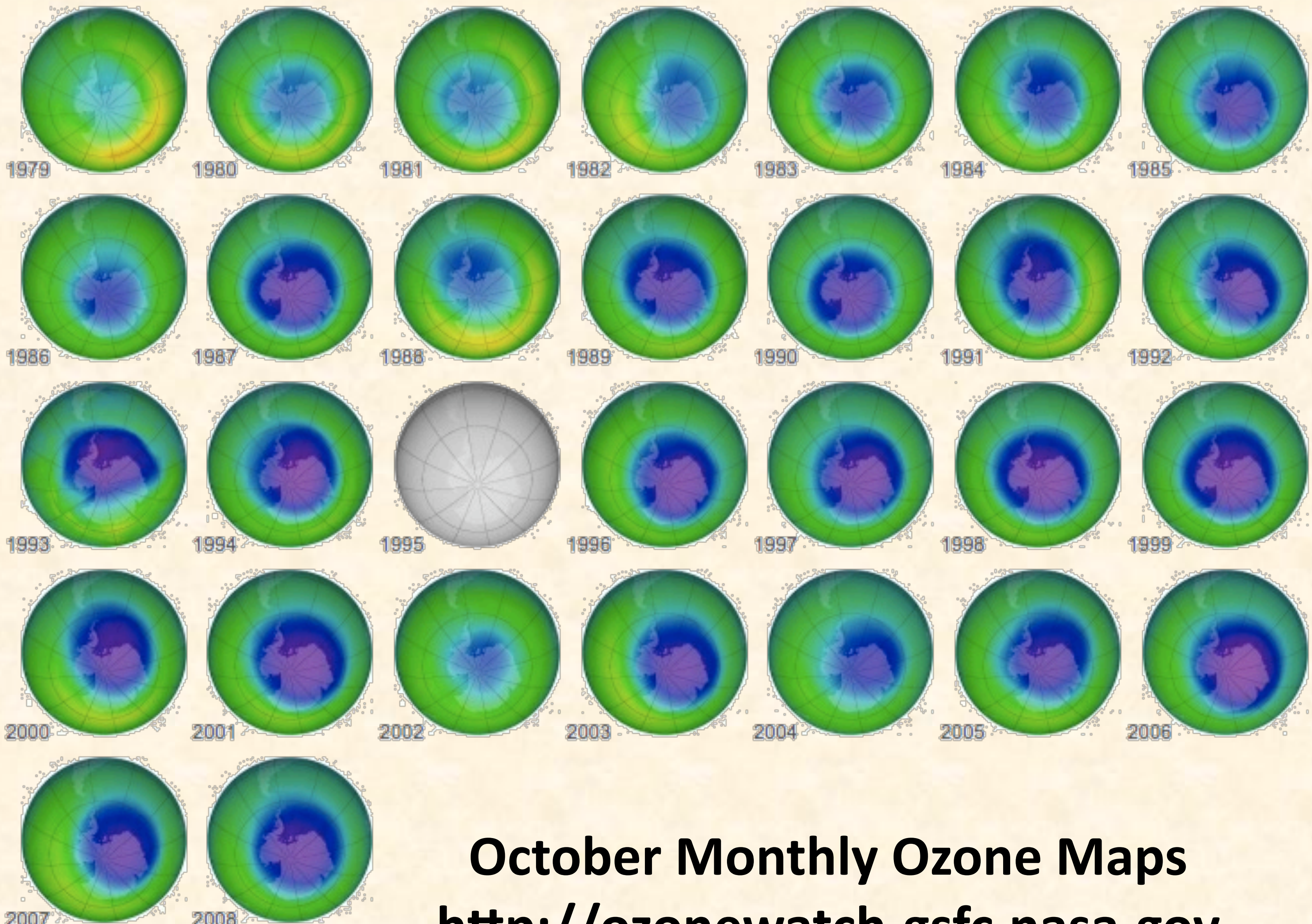
Original TOMS ozone hole map produced by Don Heath and PK Bhartia in 1985



Satellite measurements showed that Halley Bay was in best location for seeing ozone hole

TOMS MEASUREMENTS OF THE OZONE HOLE



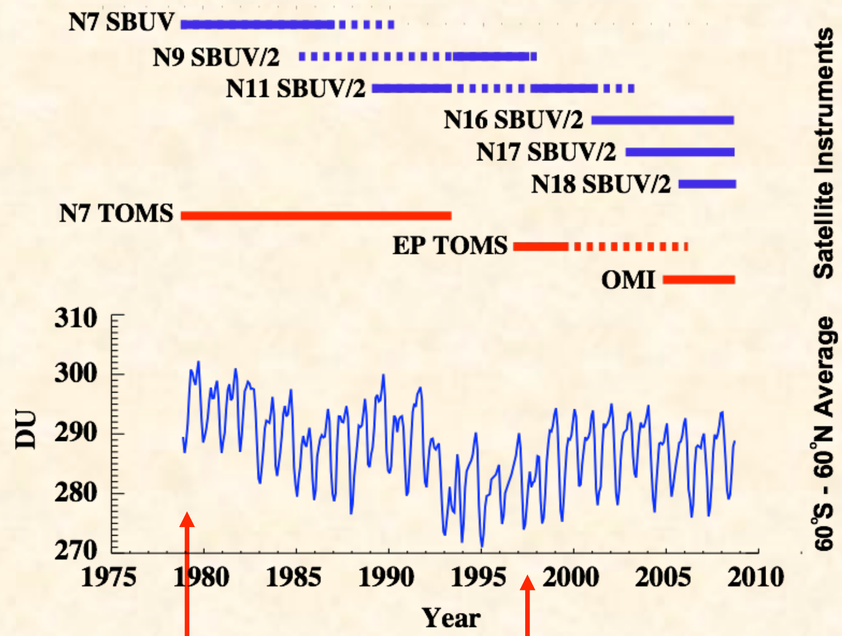


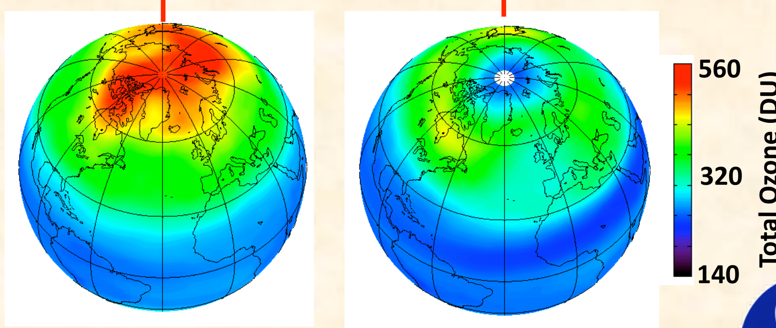
October Monthly Ozone Maps

http://ozonewatch.gsfc.nasa.gov

Global-scale ozone trends from 30 Years of TOMS and SBUV Measurements

- Global-scale ozone trends deduced from satellite measurements quantify the impact of CFCs on the stratosphere.
- Future satellite measurements are needed to observe the expected recovery of ozone in response to the Montreal Protocol.
- Backscatter ultraviolet instruments (TOMS and SBUV) have been measuring the total column amount of ozone since 1978.
- We merged the data from various satellites for the past 30 years to create this data set. We will continue to incorporate new data from SBUV, OMI, and OMPS.





March 1979 March 1997

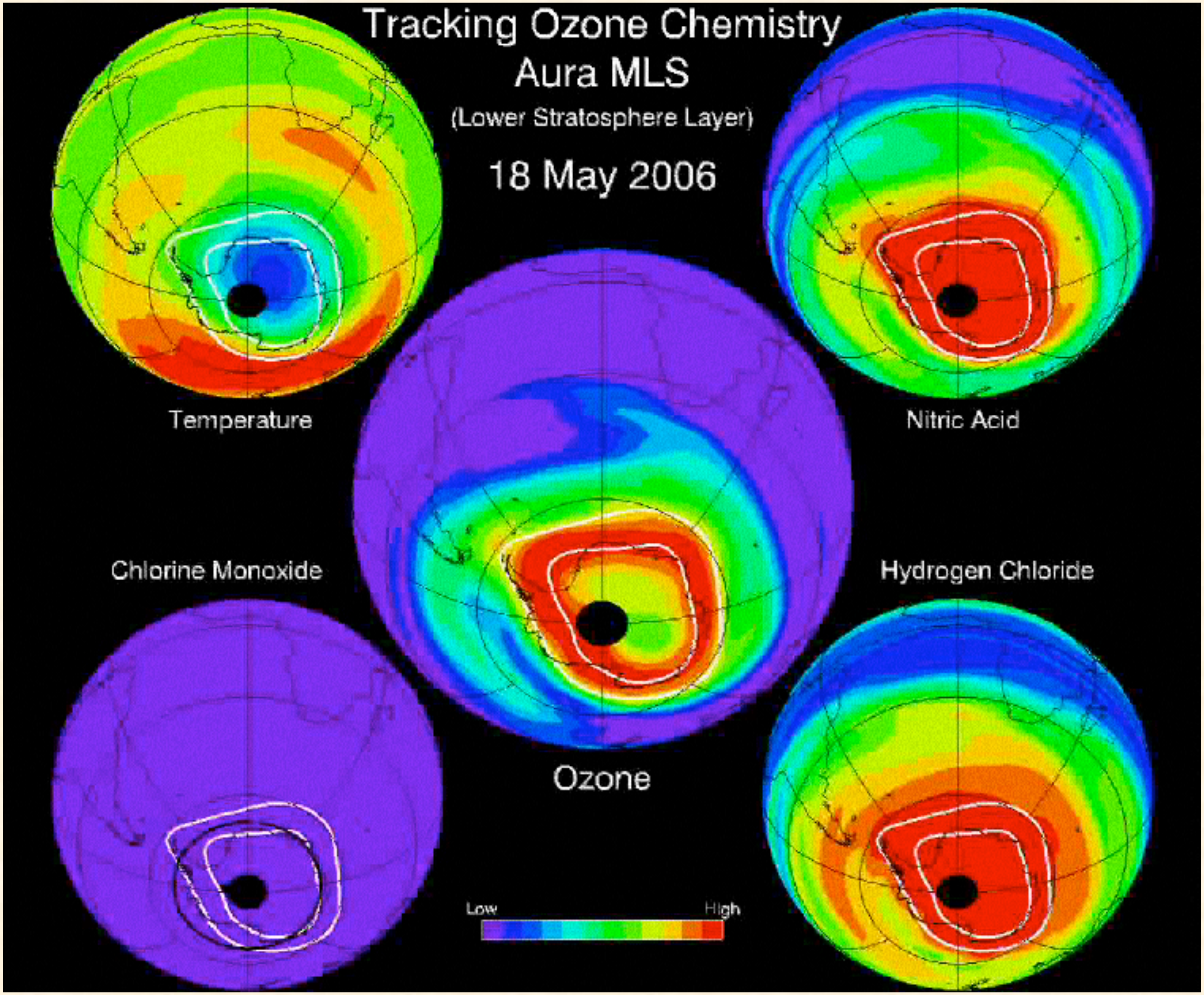
THE OZONE HOLE: A MODERN VIEW

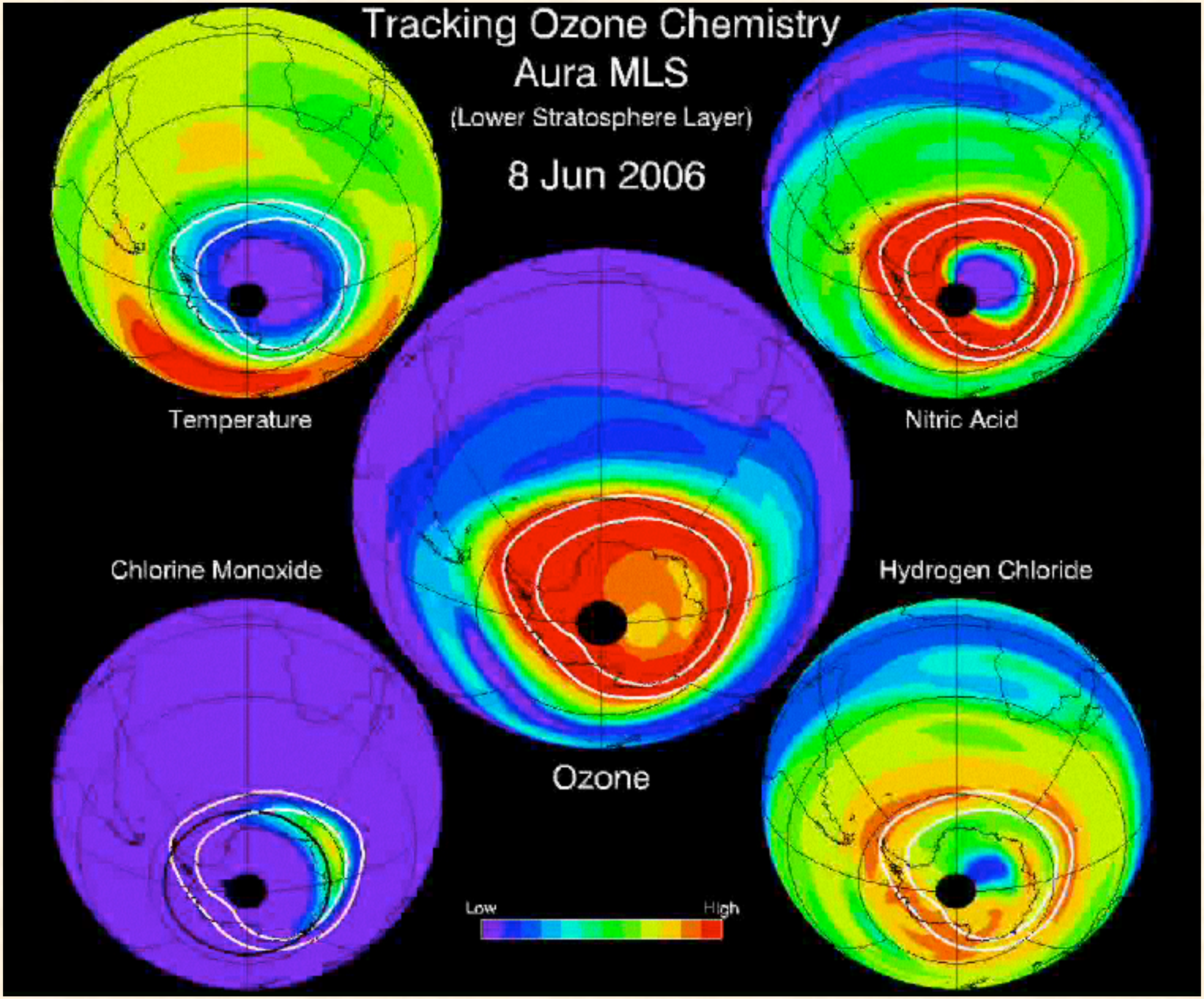
What Causes the Ozone Hole?

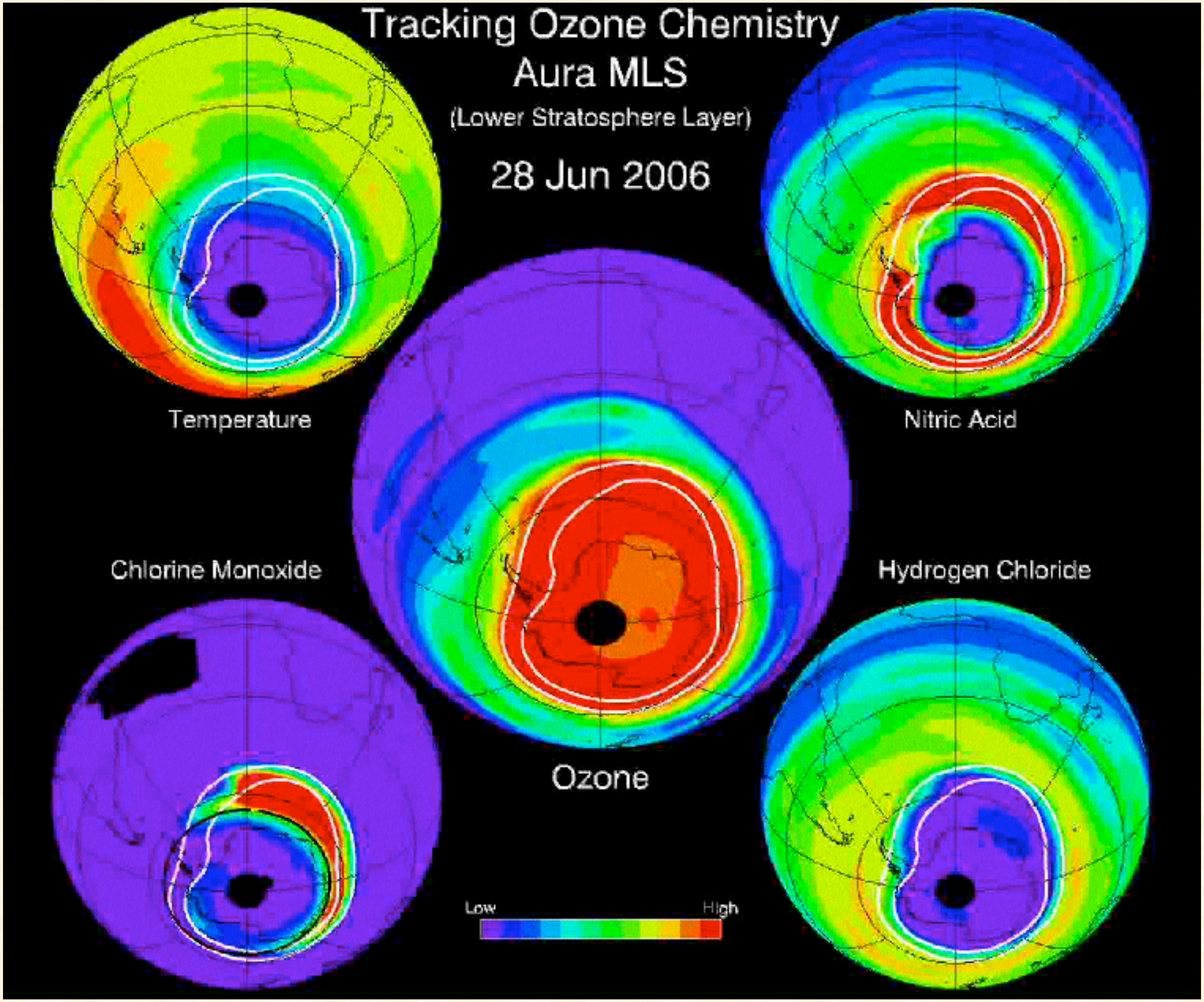
- Isolated, cold stratospheric polar vortex
- Reactions on surfaces of polar stratospheric clouds convert reservoirs, chlorine nitrate ($ClNO_3$ and HCl) to active chlorine
- Nitrogen is incorporated into particles as HNO_3 and removed
- Reactive ClO reaches > 1 ppbv concentration, self-reacts to form dimer ClOOCl
- Springtime sunlight, dimer photolyzes to form Cl atoms
- Catalytic cycle
  - $ClO + ClO \rightarrow ClOOCl$
  - $ClOOCl + h\nu \rightarrow Cl + Cl + O_2$
  - $2x\,\{Cl + O_3 \rightarrow ClO + O_2\}$
  - Net: $2O_3 \rightarrow 3O_2$

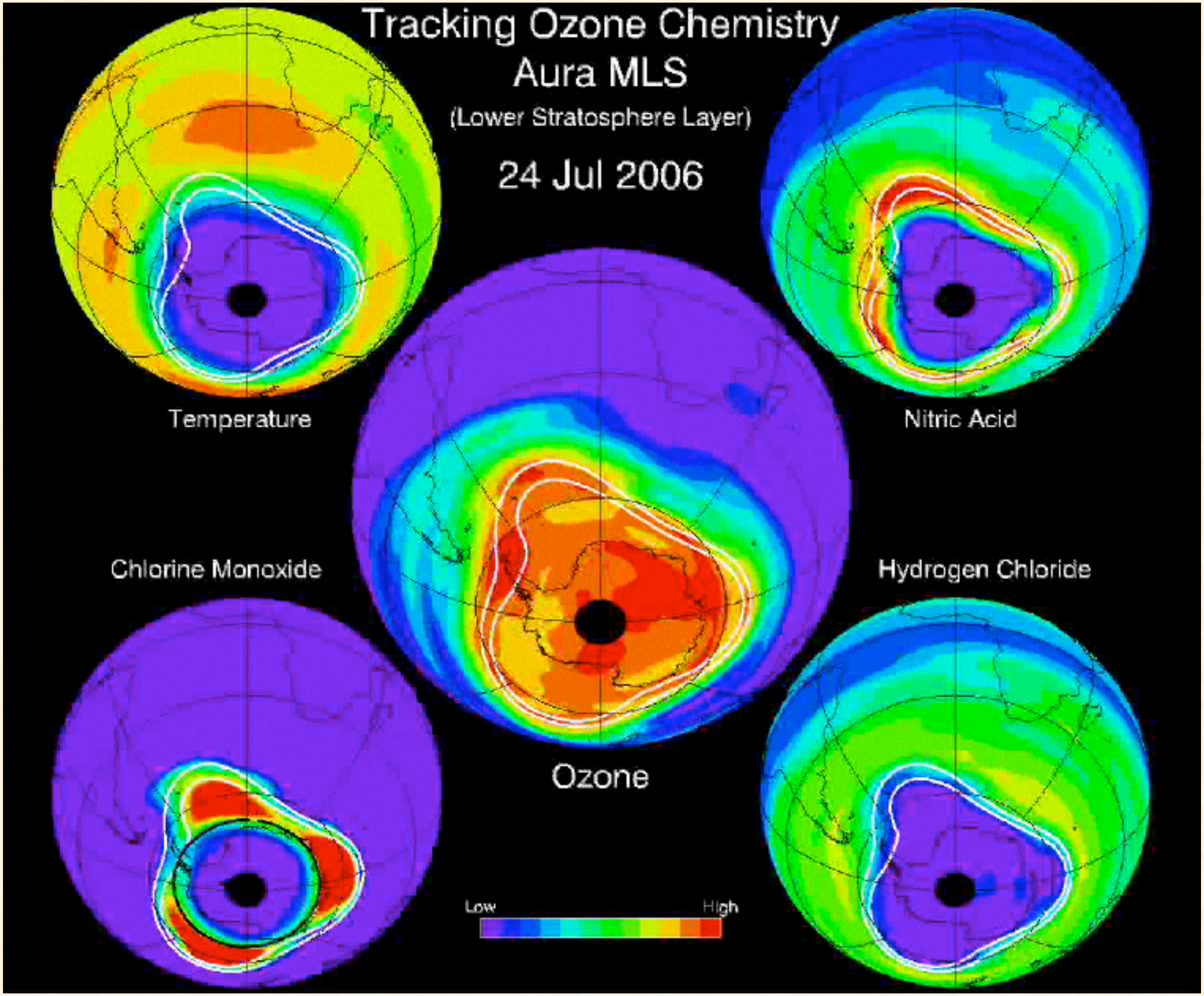
What should we be looking for?

- Chlorine nitrate ($ClNO_3$) and HCl disappear during polar night
- Nitric acid (HNO_3) should also disappear as vortex is "denitrified"
- ClO should appear as sun rises; first in outer part of vortex, then later towards pole
- Ozone should begin to rapidly decrease in sunlit ring around remaining polar night
- Ring moves inward to give entire vortex low ozone concentrations
- When ozone concentration is low enough, ClO should be rapidly reconverted to HCl (not $ClNO_3$ as in the Arctic)

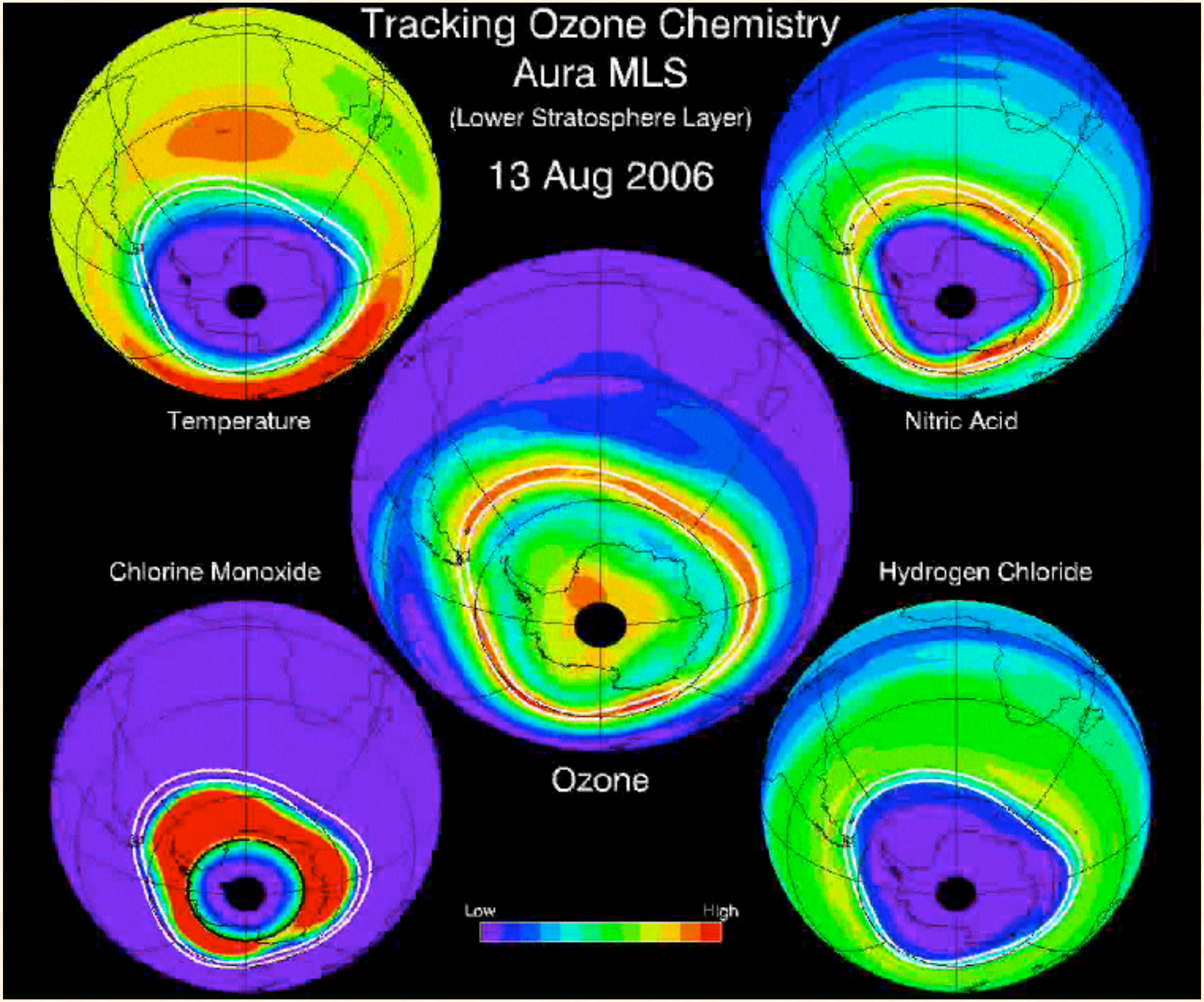

Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
18 May 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

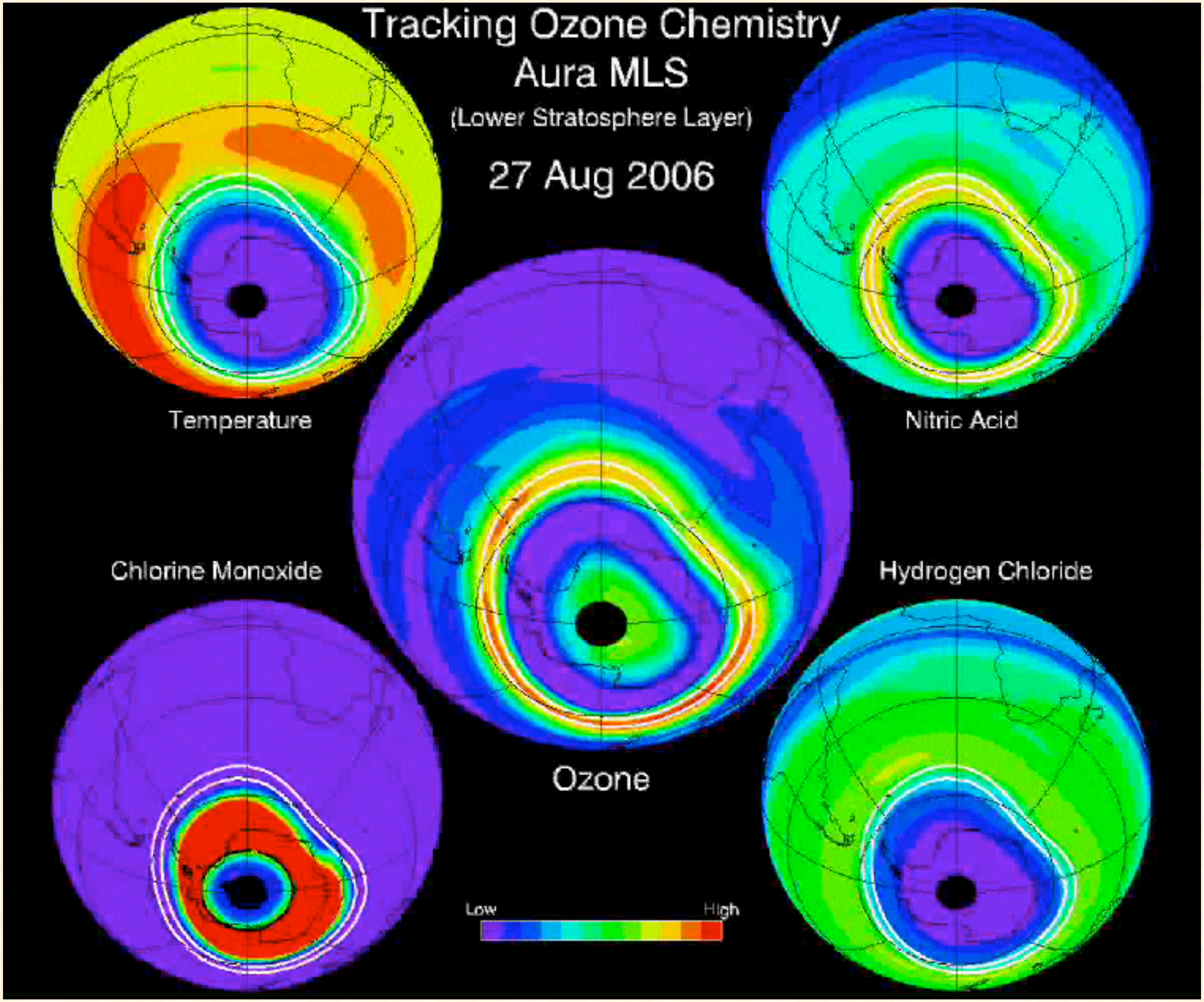

Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
8 Jun 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

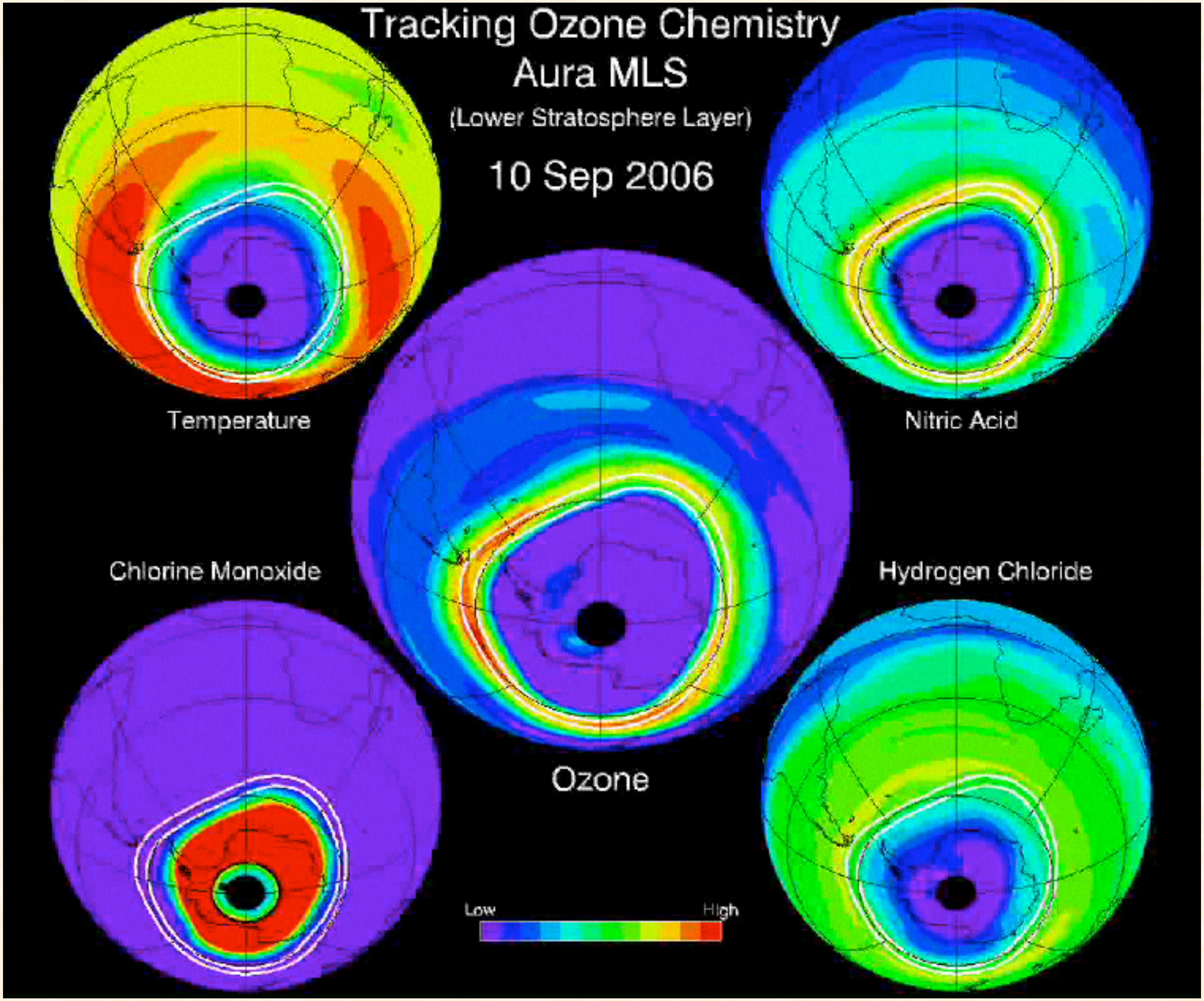

Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
28 Jun 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

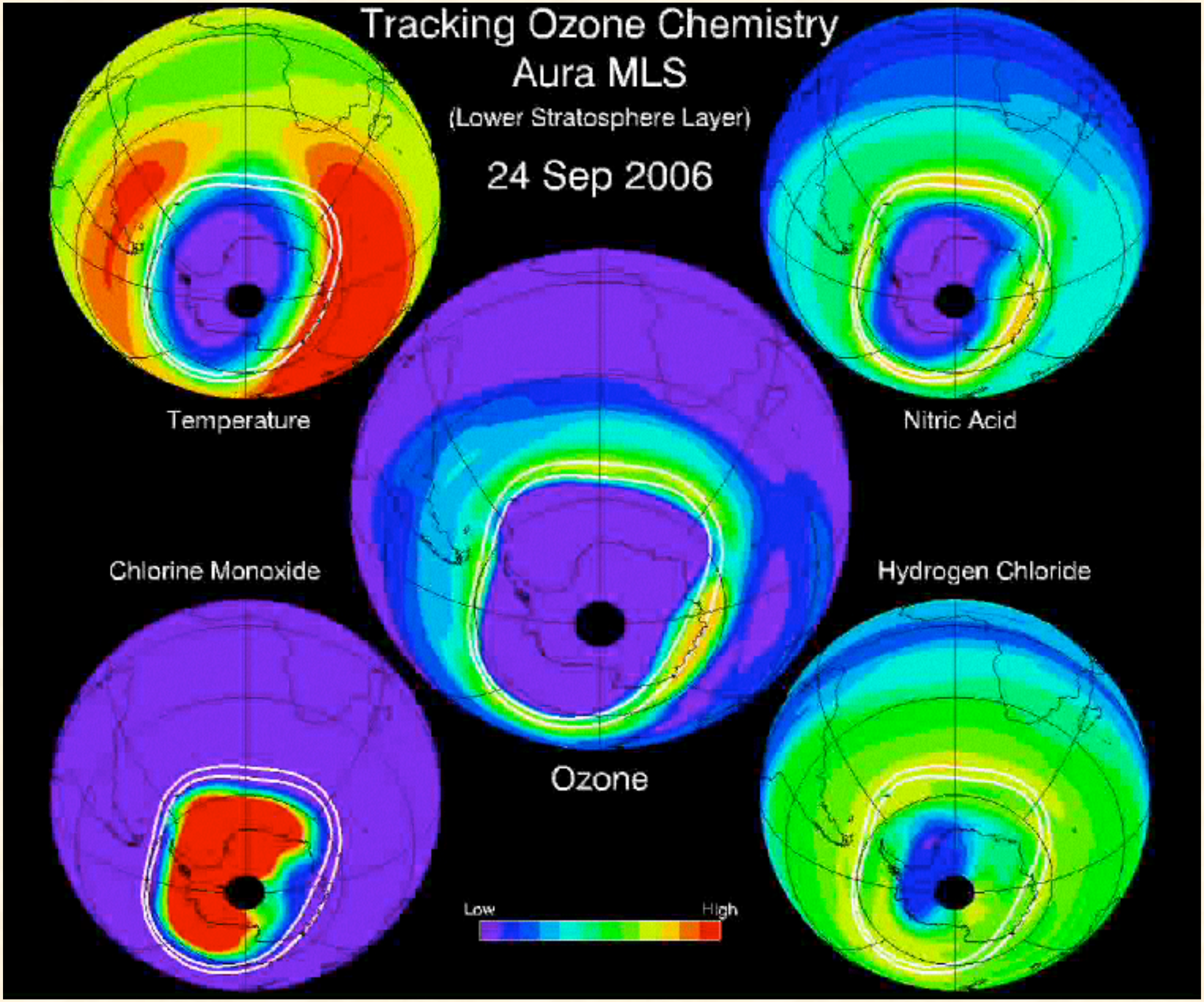


Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
24 Jul 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

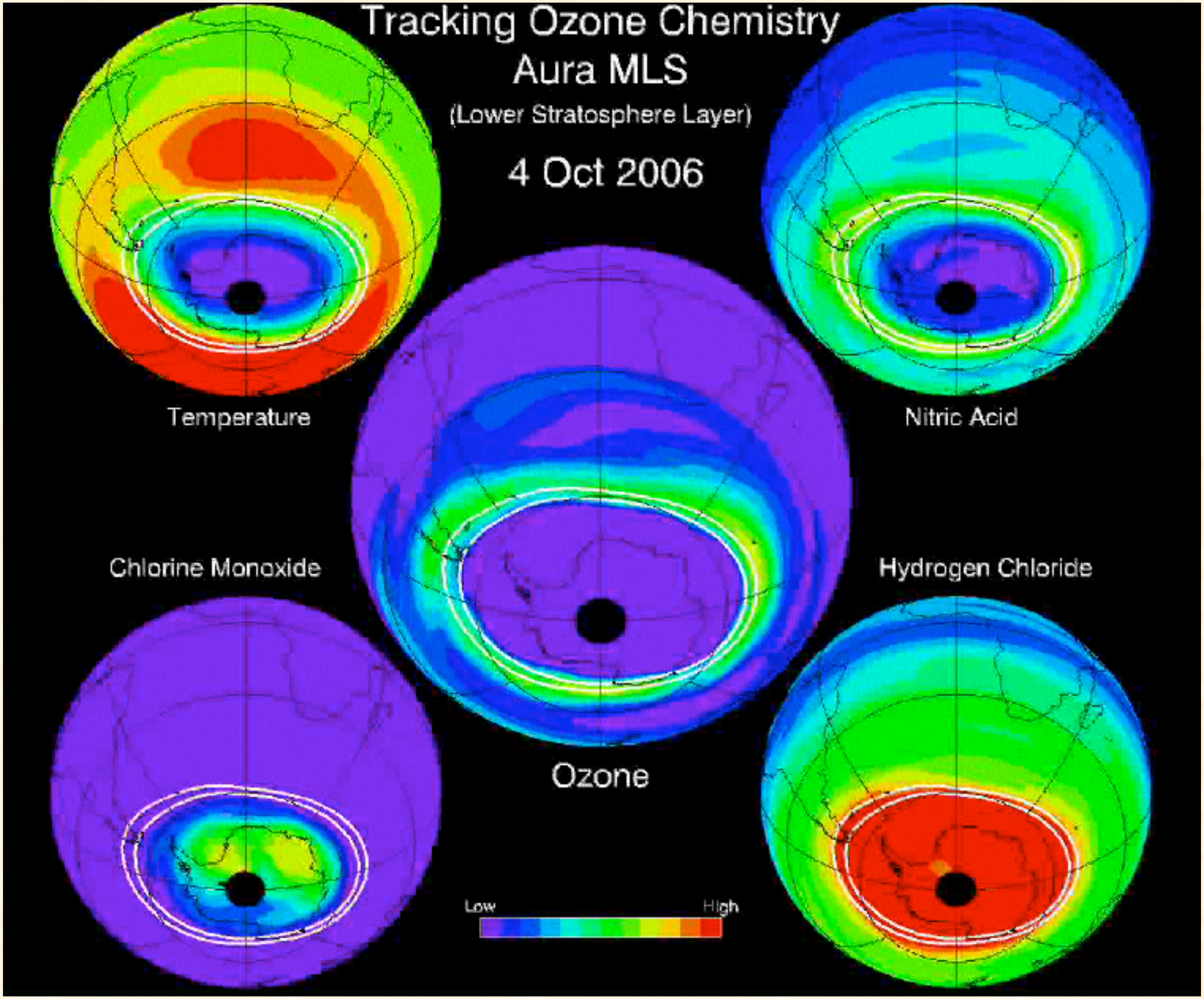

Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
13 Aug 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

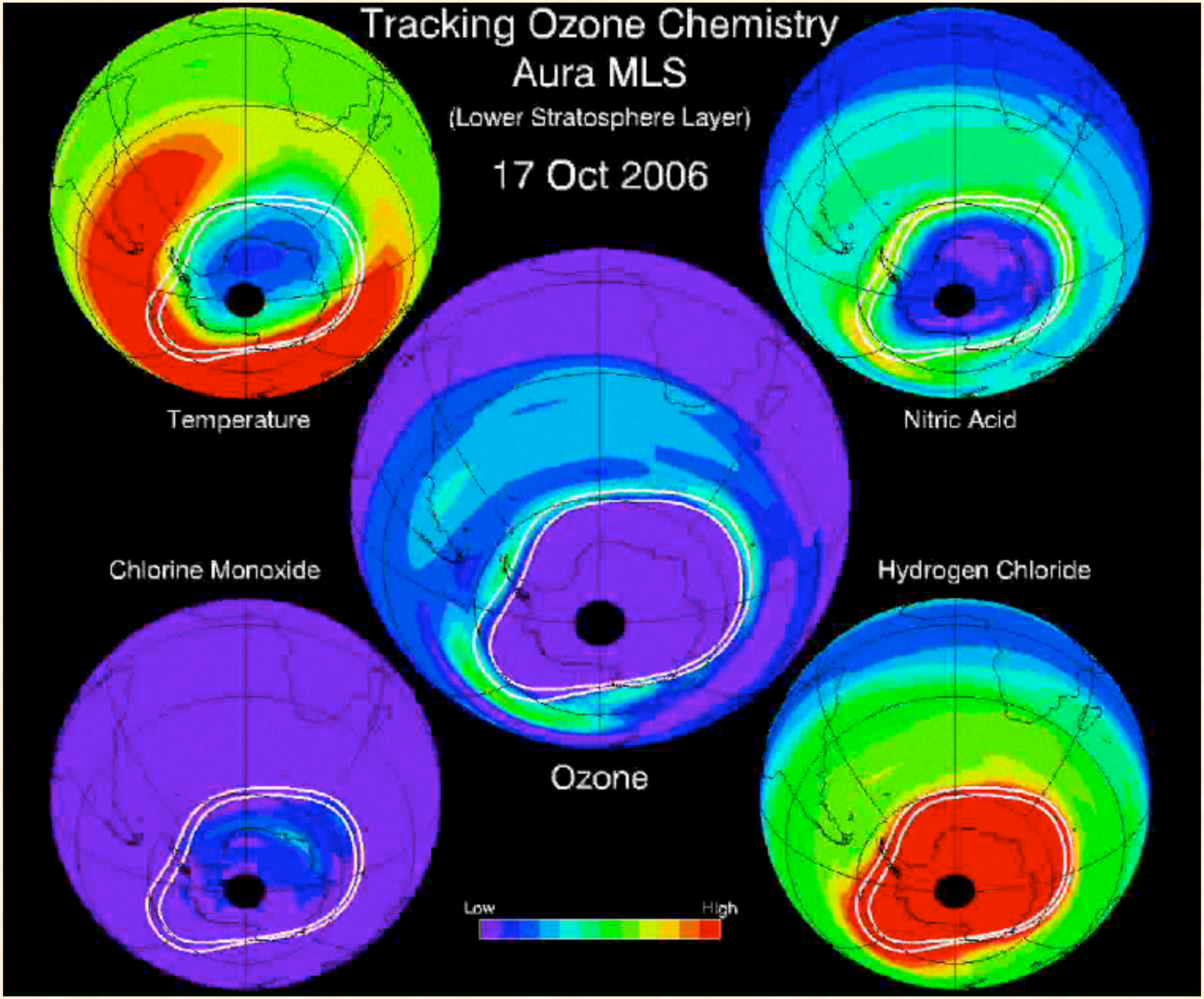

Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
27 Aug 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

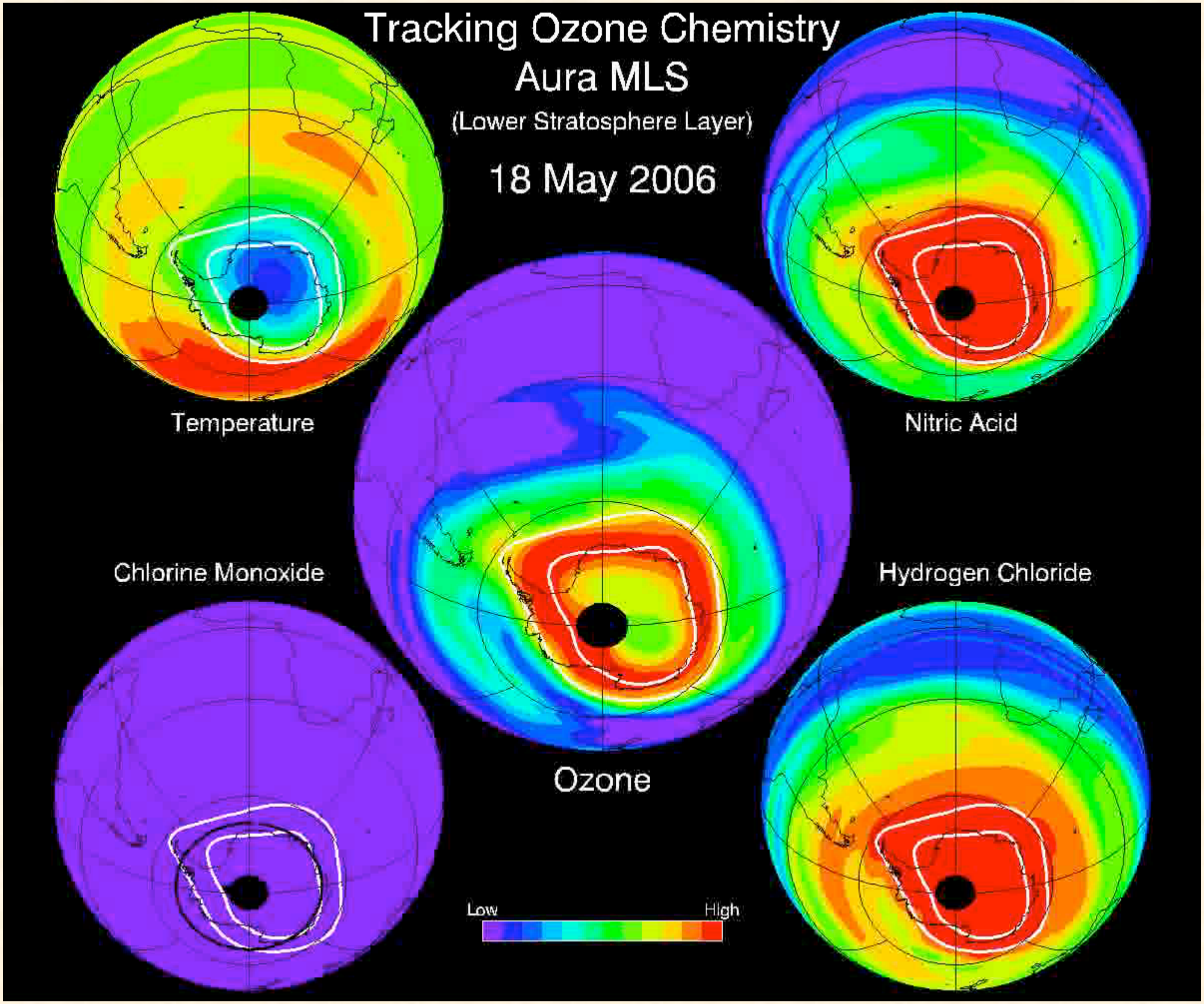

Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
10 Sep 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High



Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
24 Sep 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High


Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
4 Oct 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High


Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
17 Oct 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

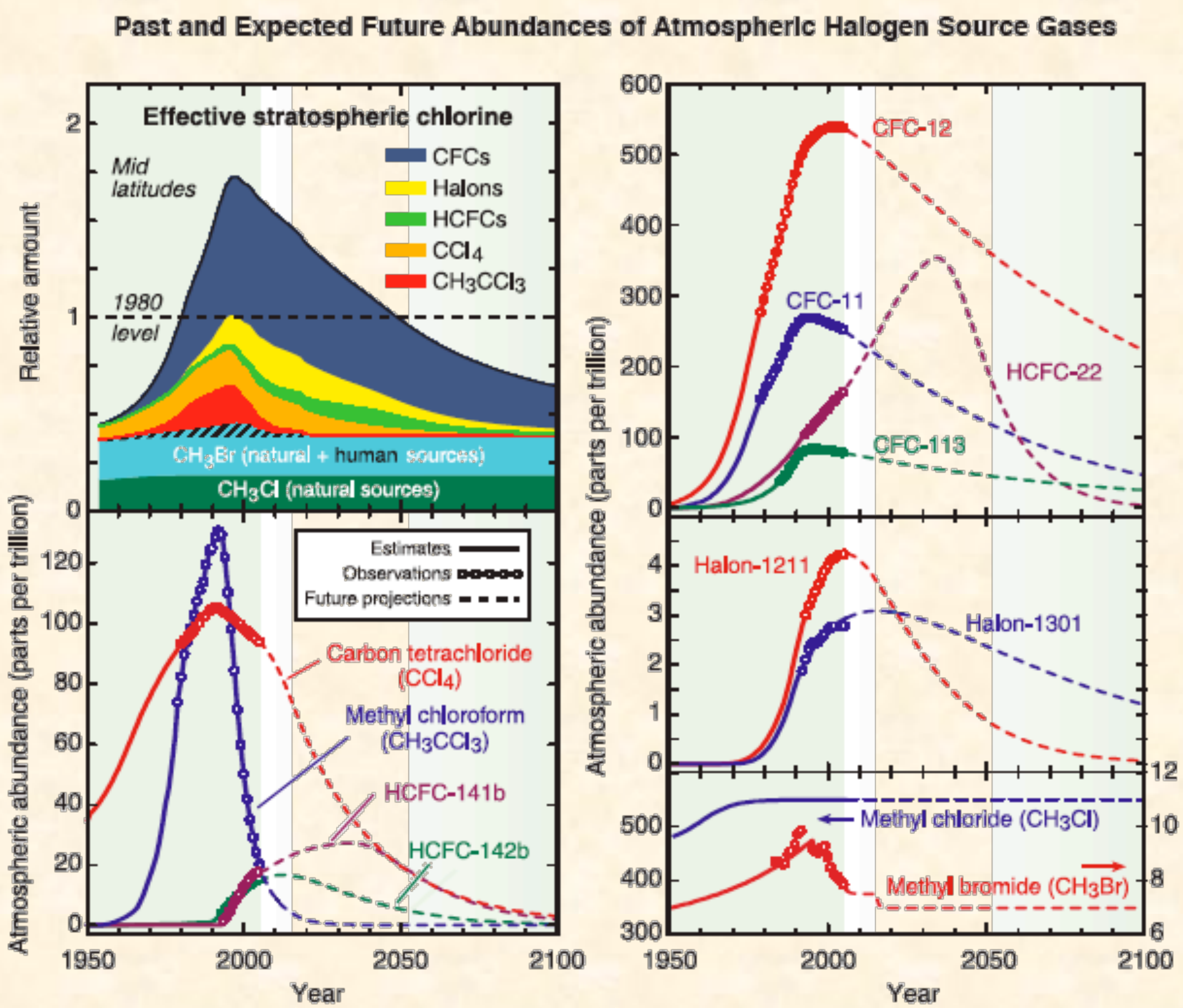


Tracking Ozone Chemistry
Aura MLS
(Lower Stratosphere Layer)
18 May 2006
Temperature
Nitric Acid
Chlorine Monoxide
Hydrogen Chloride
Ozone
Low
High

WHEN WILL THE OZONE HOLE RECOVER?

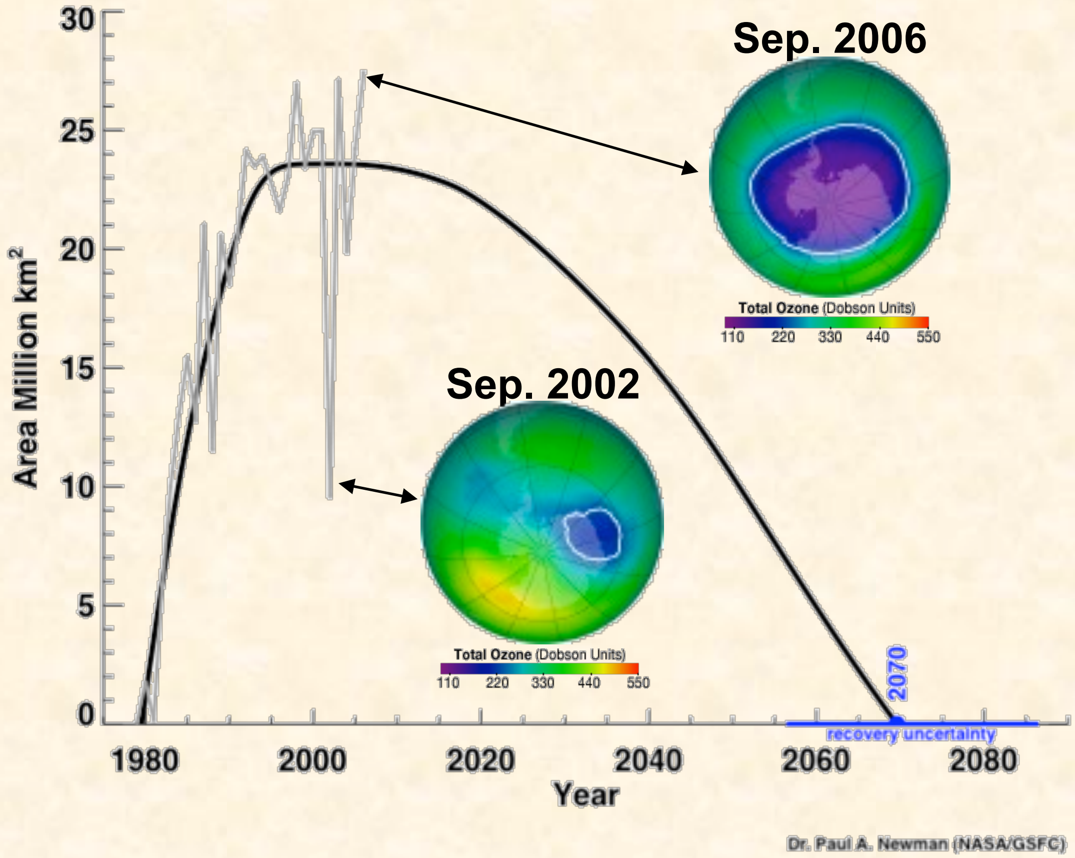
Measurements at ground stations show that the protocol is working

http://www.esrl.noaa.gov/gmd/hats/graphs/graphs.html



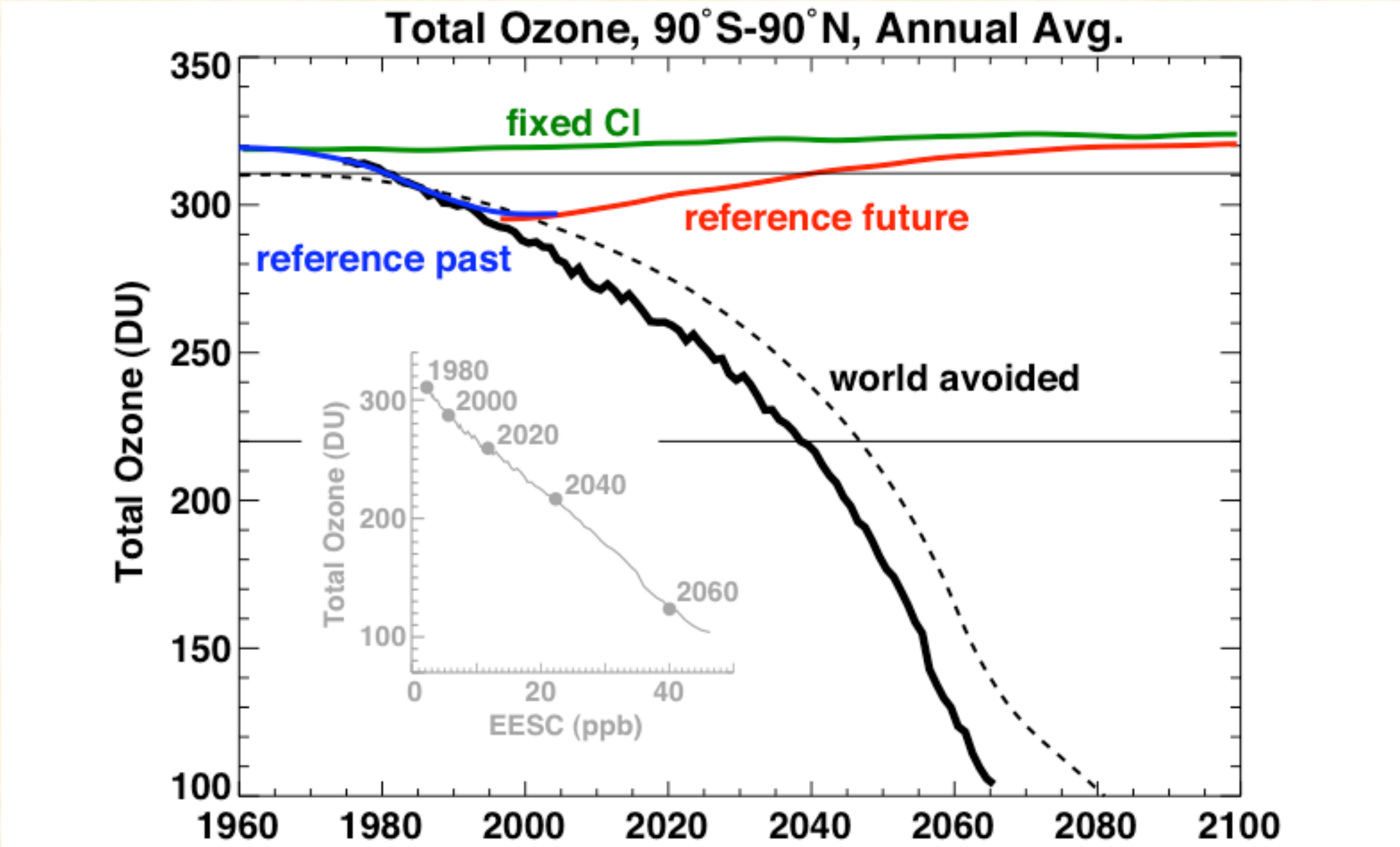
Ozone Hole Recovery

- The Antarctic ozone hole is caused by chlorine and bromine from human-produced gases.
- We have developed a parametric model of the ozone hole that is based upon satellite, ground, and aircraft observations of ozone and chlorine and bromine species.
- From this model, we estimate that the ozone hole will begin to show decreases in 2023, and will be fully recovered by 2070.
- Recent occurrences of particularly small (2002) or large (2006) ozone holes are not indicative of a long-term trend.



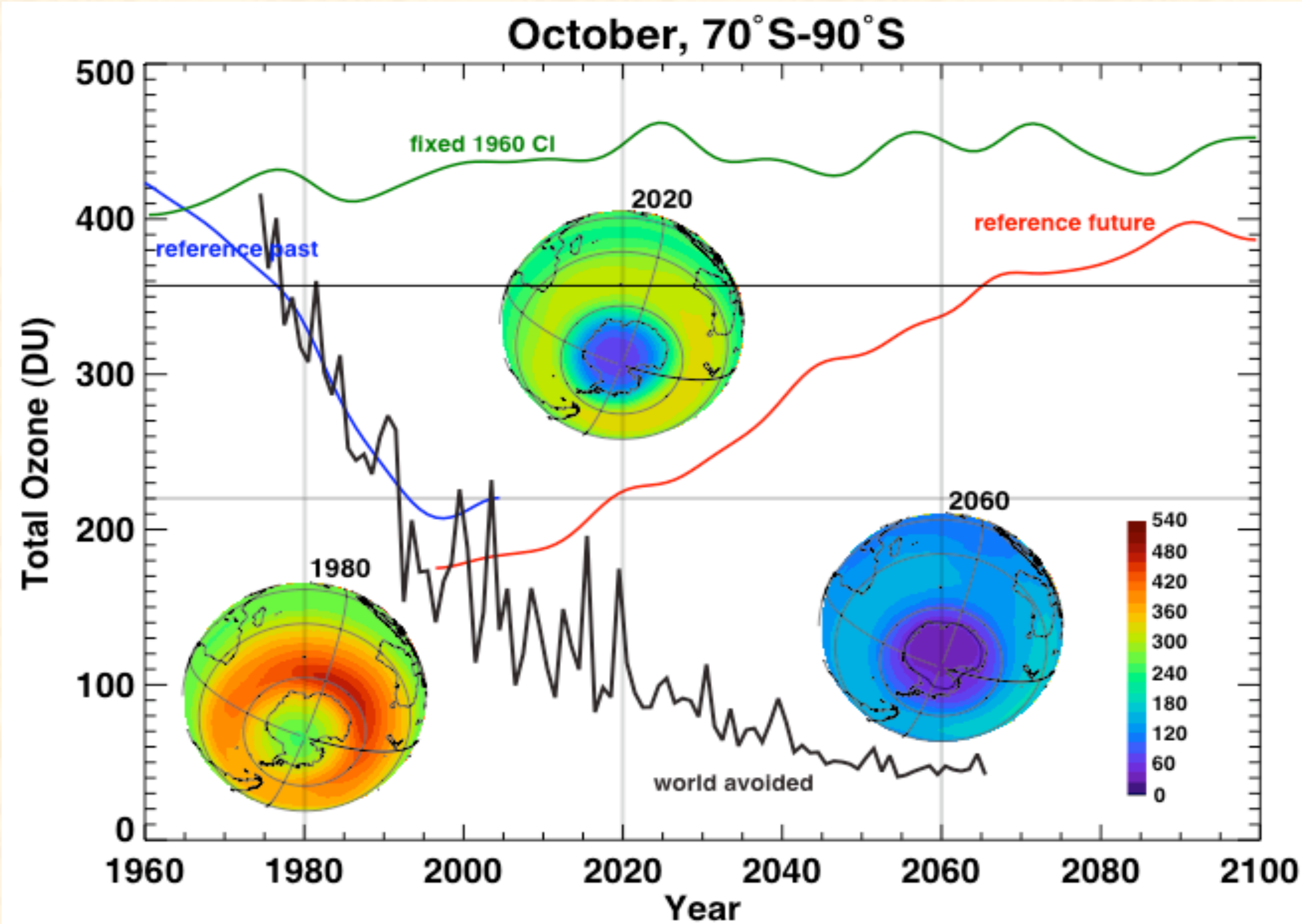
THE WORLD AVOIDED: A MODEL STUDY

Global Total Ozone



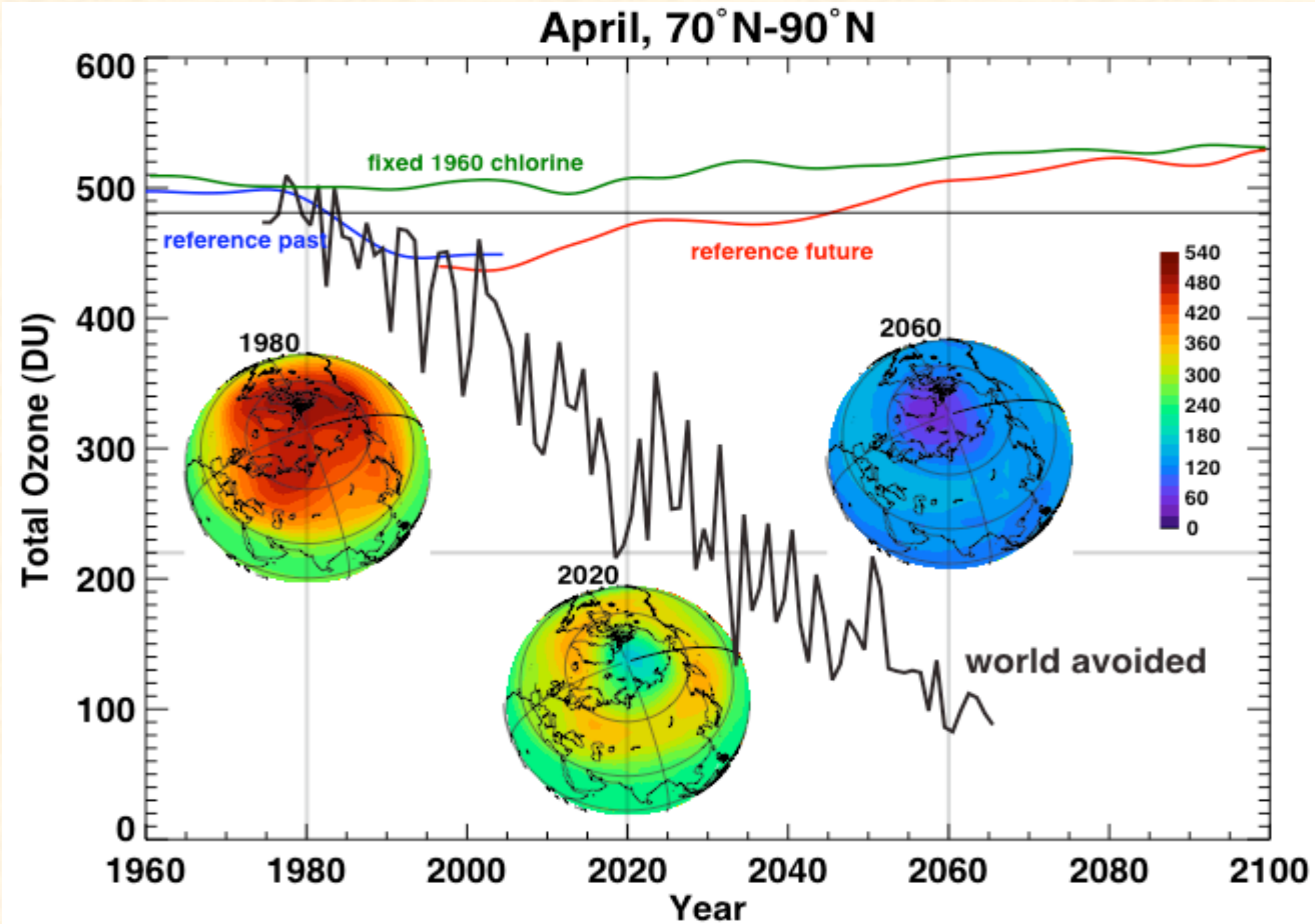
Annually averaged global ozone for the WORLD AVOIDED simulation (black), reference future (red), fixed chlorine (green), and reference past (blue). The grey shaded inset shows the same WORLD AVOIDED total ozone plotted against global annual averaged EESC at 44 hPa from summing the model Cly with the Bry scaled up by a factor of 60.

Antarctic Oct. Total Ozone



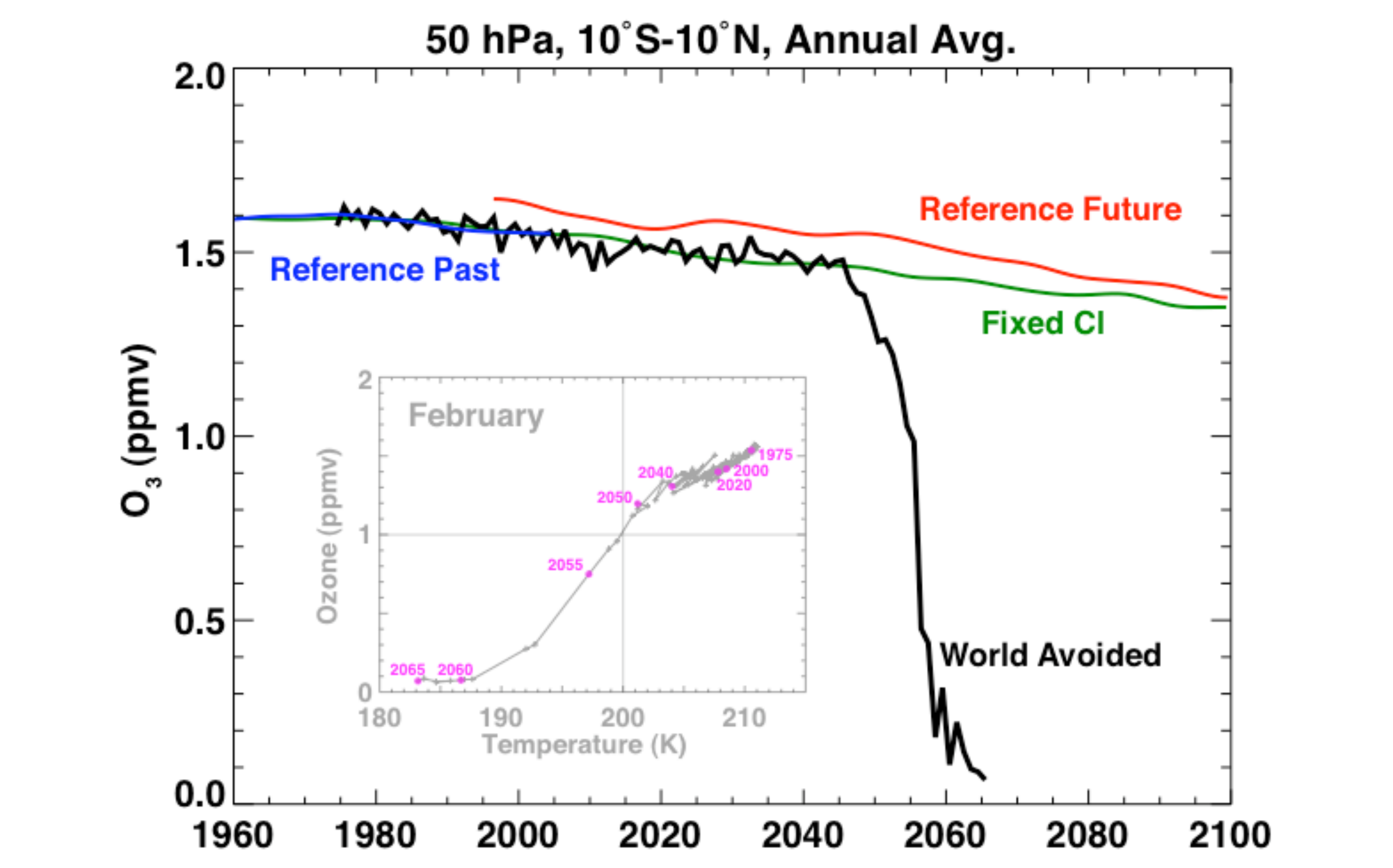
Polar total ozone is shown for the ***WORLD AVOIDED* simulation (black),** *reference future* (red), *fixed chlorine* (green), and *reference past* (blue). The *reference future*, *fixed chlorine*, and *reference past have been smoothed.*

Arctic April Total Ozone



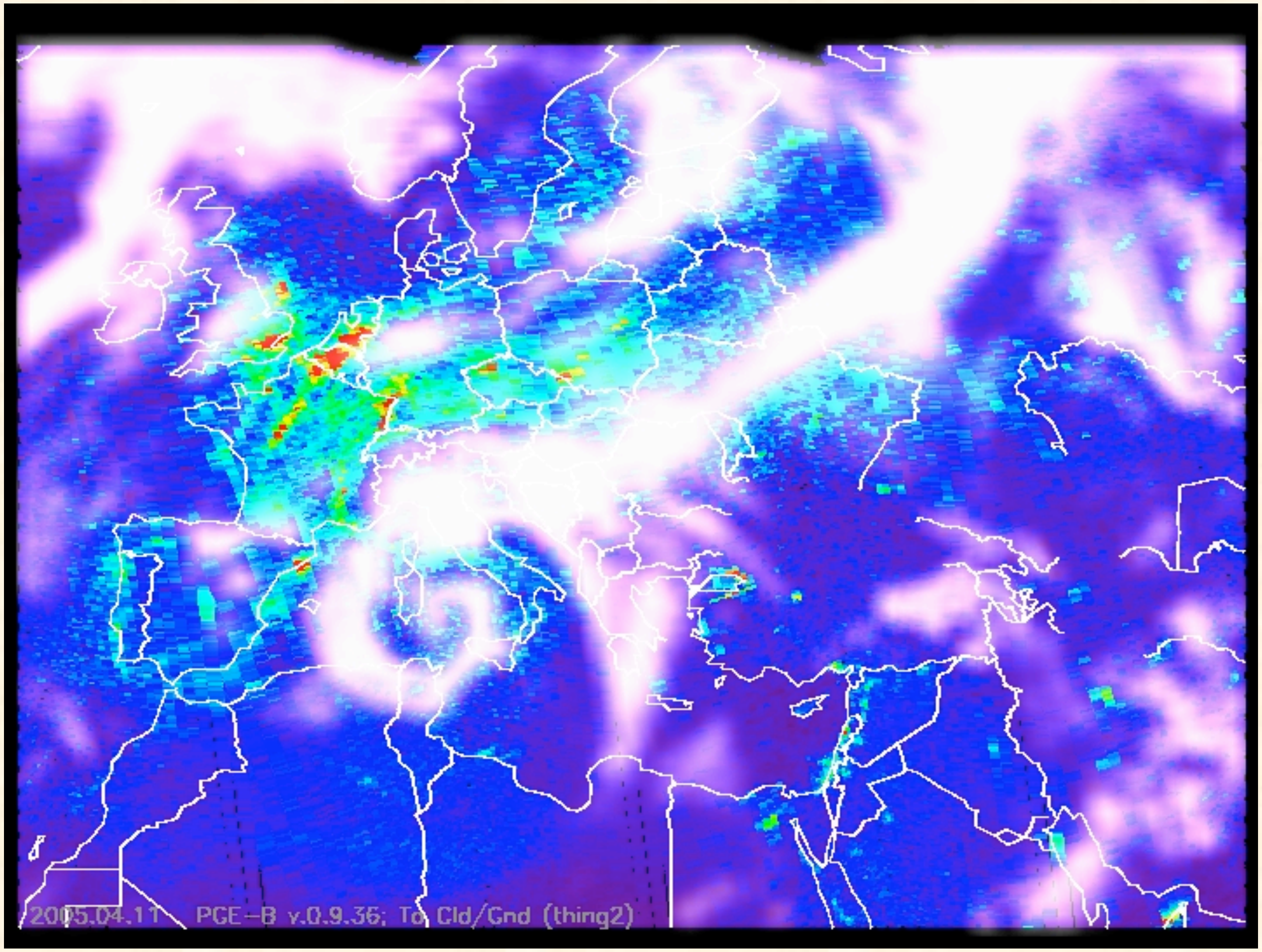
Polar total ozone is shown for the ***WORLD AVOIDED*** **simulation (black),** *reference future* (red), *fixed chlorine* (green), and *reference past* (blue). The *reference future*, *fixed chlorine*, and *reference past have been smoothed.*

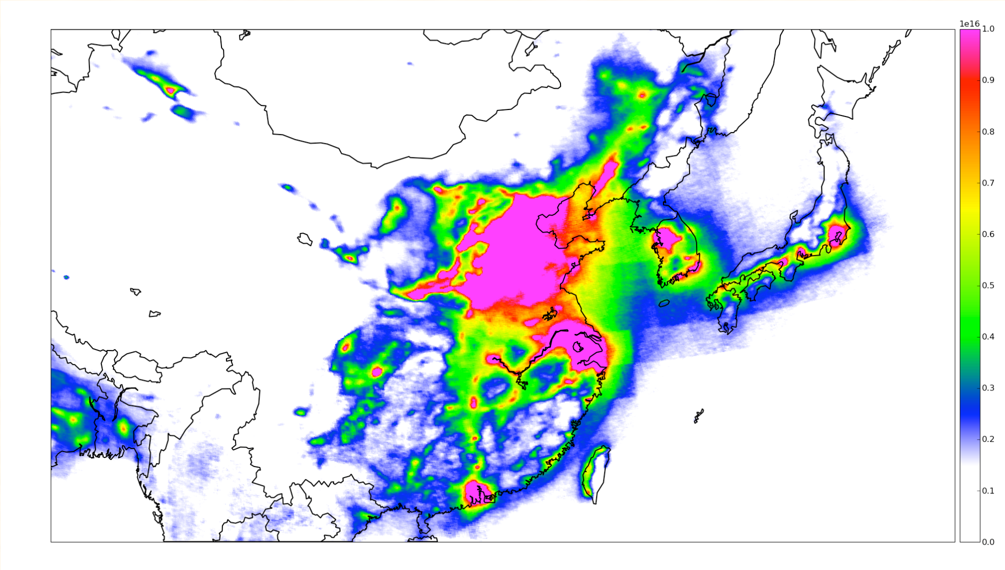
Tropical Lower Stratospheric Ozone



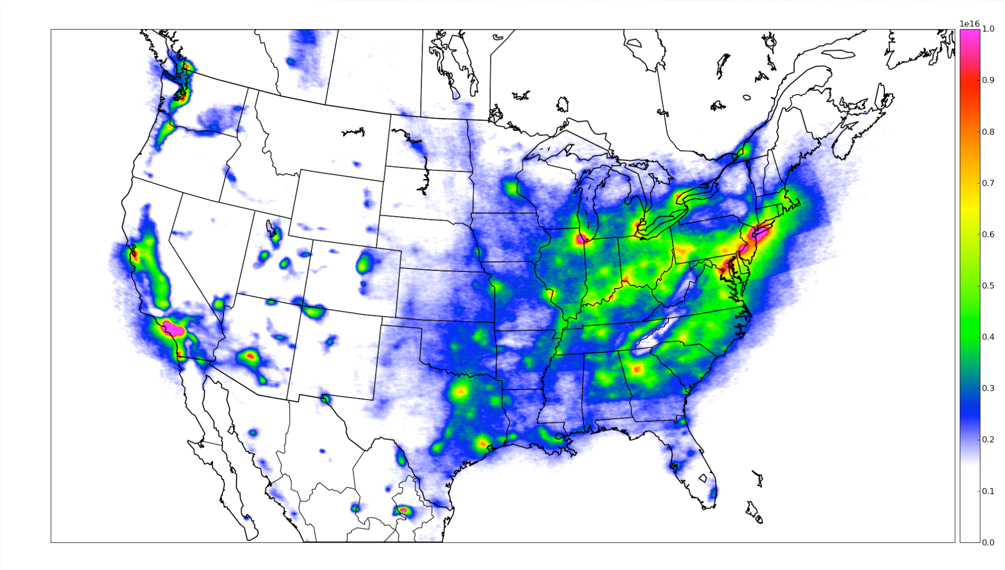
THE FUTURE: MEASURING THE TROPOSPHERE FROM SATELLITE

We can see nitrogen dioxide using the OMI instrument on Aura



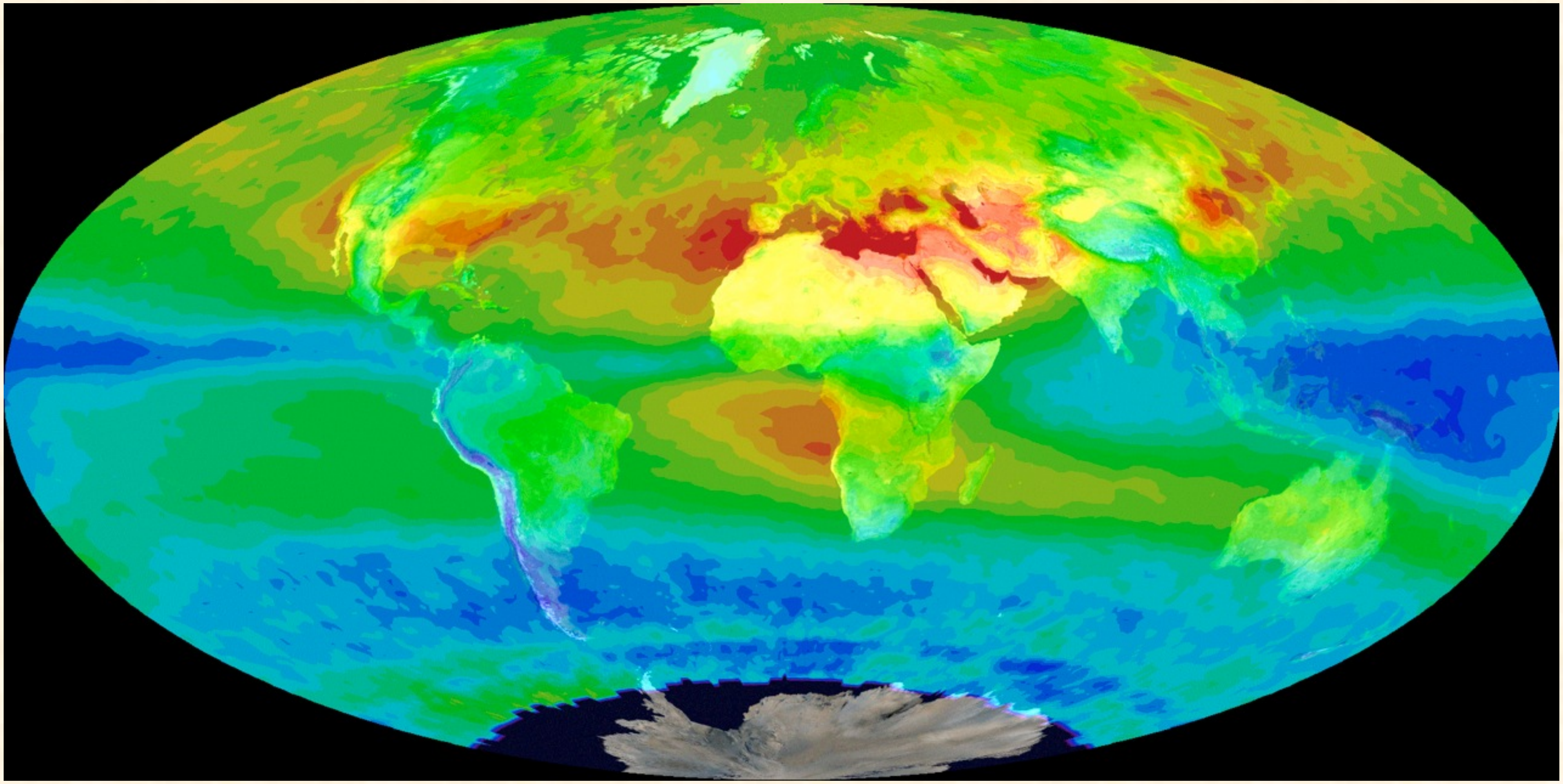


Contrast East Asia to North America



Nitrogen Dioxide (NO_2) Column

We can deduce the total column amount of ozone in the troposphere by combining OMI and MLS data from Aura



Schoeberl et al. 2009

Conclusions

- The ozone hole provided a dramatic illustration of how we can affect our environment
- The ozone hole will recover as the chlorine and bromine are removed from our atmosphere by following the provisions of the Montreal Protocol
- The rapid progress in understanding after the discovery of the hole was made possible by the development of measurement techniques that had taken place in the previous decades